Title: Energy poverty and thermal comfort in northern urban China: A household-scale typology of infrastructural inequalities

Abstract: Cities in China have undergone considerable transformation in recent decades with unprecedented economic growth, rural to urban migration and a rapidly emerging middle class all contributing to increased energy consumption. In this context, we investigate the inability of urban households in the cold climate zone in northern China to access sufficient domestic energy services, and thus their vulnerability to energy poverty, focusing upon heating provision. Results of a questionnaire survey of households in the capital city of Beijing (n=880) are analysed using Latent Class Analysis, a methodologically novel approach to developing a typology of energy poverty. The analysis highlights the existence of significant vulnerabilities that increase the likelihood of a household being unable to access adequate heating in the home in this context. Despite provision of state-subsidies for heating in cities in northern China, a mechanism that might be anticipated to buffer households from energy poverty, these do not shield from the cold those households that lack access to efficient and flexible networked infrastructures, or a high quality, built environment. Our findings represent the first detailed study of energy poverty in relation to heating in this geographical context and have significant implications for domestic policy-making concerned with energy poverty, residential energy efficiency and domestic energy consumption.

Keywords: Energy poverty; Vulnerability; Urban China; Thermal comfort; Heating infrastructure; Latent Class Analysis

1. Introduction

Since the 1970s, policies of reform and opening-up have transformed Chinese cities. The introduction of market forces has been connected with unprecedented economic growth, urbanisation and rural to urban migration, and the rapid emergence of middle class households (Wang 2014, Li 2010). Annual GDP growth between 1980 and 2017 averaged 9.66%, whilst the urban population increased fourfold (Fan et al. 2017). These trends have been accompanied by increasing energy consumption, due primarily to investments in industry and infrastructure, as between 2000 and 2014 electricity consumption grew on average by 10% per annum (Lin and Liu 2016). Residential energy consumption has also risen as processes of urbanisation have enabled and necessitated an increasingly 'electrified livelihood' (Wang 2014) with greater demand for domestic energy services and larger living areas (Shan et al. 2017). Domestic heat consumption increased by 3.66 times between 1996 and 2012 (Fan et al. 2017).

Living conditions have subsequently improved with reductions in multidimensional poverty (Fan et al. 2004, Yu 2013). However, relative inequalities have increased and remain high by international standards (Li and Sicular 2014, Xie and Zhou 2014), especially related to wealth distribution (Xu and Wang 2017). One inequality that has received limited attention is the inability of households to access sufficient domestic energy services. The achievement of adequate thermal comfort, through heating and cooling, and access to other socially necessitated energy services, including cooking and washing, has substantial benefits for health and wellbeing (Liddell and Morris 2010) in addition to wider socio-economic development goals (Sovacool 2012). The condition of being without essential energy services, energy poverty, has been widely researched (Li et al. 2014, Bouzarovski and Petrova 2015, Thomson and Snell 2013) due to the social justice imperatives associated and the role that the inefficient consumption of energy by the energy poor plays in achieving climate change targets (Urge-Vorsatz and Tirado-Herrero 2012) and reducing harmful localised air quality (Zheng et al. 2015).

The aim of this paper is to investigate inequalities in heating provision, and thus vulnerability to energy poverty, amongst households in the case study city of Beijing, where low winter temperatures necessitate a high level of heating to maintain health and wellbeing. Whilst our analysis concentrates upon Beijing, a city of relative affluence, it also provides insight into energy poverty across northern urban China where similar heating policies exist. This follows recent efforts to measure energy poverty in a diverse range of geographical settings (e.g. Sadath and Acharya 2017, Okushima 2016, Papada and Kaliampakos 2016, Teller-Elsberg et al. 2016). It also responds to a call from Browne et al. (2017) to explicitly consider the ways in which vulnerabilities and inequalities are produced across, and within, Chinese regions and cities in relation to energy. Fulfilment of this aim provides insight into a geographical context underexplored in relation to energy poverty and highlights marginalised spaces in the city region concerning heating provision. Our findings have significant implications for domestic policy-making related to energy poverty, energy efficiency and domestic energy consumption, and subsequently reductions in carbon emission and harmful particulates. The analysis also makes a novel methodological contribution representing the first application of Latent Class Analysis (LCA), a means of identifying clusters within categorical datasets, to understanding energy poverty.

The paper is structured as follows. The term energy poverty is defined and existing studies of energy poverty in China are discussed in sections two and three. This is followed by an introduction to the case study of heating Beijing in section four. Our methodological approach, using a household questionnaire survey and LCA, is outlined in section five. Section six presents descriptive statistics from the survey before section seven outlines the LCA results, a typology of vulnerability to energy poverty in relation to thermal comfort. In section eight we discuss important features of vulnerability to energy poverty in this context with reference to existing policy mechanisms.

2. Energy poverty: Why does it matter and how can we define it?

Li et al. (2014) outline how energy poverty has attracted considerable attention over several decades in research and policy-making in both the Global North (Boardman 1991, Buzar 2007, Thomson and Snell 2013) and the Global South (e.g. Nussbaumer et al. 2012, Sagar 2005). In the Global North (where the term fuel poverty is commonly used), research has often focused upon the health impacts of living in a cold home (Boardman 1991, Rudge and Gilchrist 2007). The World Health Organisation recommends a healthy indoor temperature of 18°C in bedrooms and 21°C in the living area. Cold homes can cause and enhance numerous health conditions, especially amongst young children, the older old and those with pre-existing condition or disability (Liddell and Morris 2010, Snell et al. 2015). Negative impacts upon mental health are also documented, in addition to reduced educational attainment (Liddell and Morris 2010), poorer social relations (Middlemiss and Gillard 2015) and a reduction in living space (Brunner et al. 2012). More recently a global perspective on energy poverty has also drawn attention to the negative impacts of being without a wider range of socially necessitated energy services beyond heating, including cooling, lighting and appliances (Bouzarovski and Petrova 2015).

In the context of the Global North, the vulnerability of a household to experiencing energy poverty tends to be increased by high energy prices that intersect with low incomes (Boardman 1991). In addition, in distinguishing energy poverty as a separate phenomenon from poverty, attention has been drawn to the important role of infrastructures. This encompasses networked infrastructures that supply reliable and affordable energy to the home, such as electricity, gas or district heating (Graham and Marvin 2002, Harrison and Popke 2011). It also refers to the quality and efficiency of the built environment that determines ability to retain energy, primarily heating (Boardman 1991, 2010). In the Global South, a wider spectrum of problems manifest due to inadequate access to energy services, negatively impacting upon social welfare, health and gender empowerment (Pachauri and Spreng 2004, Sagar 2005, Sovacool 2012). Significant negative impacts upon health have occurred due to indoor air pollution from the use of solid-wood fuels for cooking (Sovacool 2012). The likelihood of experiencing energy poverty in this context is primarily enhanced by low levels of electrification and networked energy provision due to economic underdevelopment and dysfunctional institutions (Bouzarovski and Petrova 2015).

Whilst preventing negative outcomes for wellbeing and realising social justice imperatives (Walker and Day 2012), alleviation of energy poverty also has synergies with climate change mitigation efforts (Urge-Vorsatz and Tirado-Herrero 2012). The energy poor, although consuming relatively low amounts of energy, tend to be the most inefficient domestic consumers per pound of fuel, due to the disproportionate loss of energy by inefficient fuels or infrastructures (Boardman 2010). Meanwhile, the residential building sector offers one of the largest and most cost-effective opportunities for reducing carbon emissions (Lucon et al. 2014). As such, deep retrofitting of the properties of energy poor households stands to make a significant contribution to the achievement of climate change goals when considered alongside occupant behaviour (Hong et al. 2016), cultural norms (Wilhite et al. 1996) and possible rebound effects (Greening et al. 2000). In some instances, an increase in domestic energy efficiency can also contribute towards a reduction in harmful, localised air pollution (Zheng et al. 2015).

Although the negative outcomes and drivers of energy poverty vary considerably between different demographics and geographical contexts, Bouzarovski and Petrova (2015) argue that the differing experiences of energy poverty globally are underpinned by a common condition. They offer a universal definition of energy poverty as 'the inability to attain a socially and materially necessitated level of domestic energy services' (Bouzarovski and Petrova 2015: 31) recognising how households desire an affordable, reliable and accessible energy supply. This definition accounts for a range of domestic energy services considered necessary that might include heating, cooling, lighting or cooking. Like many definitions of income poverty, experience of energy poverty within a household is relative and therefore the ability to achieve a sufficient supply of energy is conditioned by the society that they are part of. In addition to defining the condition, Bouzarovski and Petrova (2015) recognise that the achievement of an affordable, reliable and accessible energy supply can be prevented by a series of vulnerability factors (see also Middlemiss and Gillard 2015). Vulnerability factors cause the ineffective operation of the socio-technical pathways that allow a household to fulfil their energy needs, thus increasing the likelihood of a household falling into energy poverty. They include:

- the role of networked and capital energy infrastructures concerning both a household's access to appropriate infrastructures (Graham and Marvin 2002) and their energy efficiency (Boardman 1991)
- the affordability of energy in relation to a household's income, the market price of energy and the upfront costs of installing new energy infrastructures (Boardman 1991)
- the differential need for energy in a household due to factors such as age, health or culture, factors that often misalign with the energy services available (Snell et al. 2015)
- the household practices that determine how efficiently energy is used (Strengers and Maller 2011)
- the flexibility of a household to change how it consumes energy to meet its needs (Bouzarovski 2015)

The nature and relative contribution of vulnerability factors to a household's experience of energy poverty varies between different national contexts, regions, neighbourhoods and households, and vulnerability factors are therefore highly socially and spatially variable (Bouzarovki et al. 2017). Due to its applicability globally, the analysis that follows draws upon this conceptualisation of vulnerability to energy poverty.

3. Existing energy poverty policy and research in China

Given the significant challenge of reducing carbon emissions and curtailing dangerous localised air pollution, especially in large urban conurbations, China has a vision for sustainable economic growth facilitated through a raft of policies and legislation. Ambitious climate change goals have been set that are predicted to be overachieved, including reducing CO2 emissions per unit of GDP by 40-45% of the 2005 level by 2020 and reaching peak emissions by 2030. As part of this, building energy conservation measures have been legislated for to promote energy efficiency and reduced energy demand. In 2013 two significant regulations were introduced, the 12th Five Year Plan for the development of energy conservation and a new national standard for building energy consumption (Hong et al. 2015). In addition, Heating Reforms have been proposed intended to reduce government energy subsidies and encourage energy efficiency (Lin and Jiang 2011). However, despite interrelations with the successful mitigation of climate change and air pollution, energy poverty has rarely been the subject of domestic policymaking, besides recognition of the possible negative implications of Heating Reforms for low income consumers (Lin and Jiang 2011).

A small amount of research has sought to understand energy poverty in China. Wang et al. (2015) contend that energy poverty in China shares characteristics with the condition as understood in the context of both the Global North and the Global South. In evaluating energy poverty nationally, the study recognises that energy poverty in terms of a lack of access to electricity has largely been resolved. 98.7% of rural Chinese households have access to electricity due to state-sponsored, rural electrification and anti-poverty projects since the 1980s (Bhattacharyya and Ohaire 2012). Developing a multi-faceted energy poverty index, Wang et al. demonstrate that whilst energy poverty nationally has been alleviated over several decades, different challenges exist between different regions. One of the starkest differences in experience of energy poverty, and indeed many other inequalities in China, is between rural and urban areas, particularly in relation to cooking and heating. Research in the context of China has tended to focus upon energy poverty amongst rural households (Demurger and Fournier 2011, Pachauri and Jiang 2008, Tang and Liao 2014) where over 70% of households rely on solid fuels for cooking, resulting in indoor air pollution and negative health impacts (Liao et al. 2016). Meanwhile urban areas, where most households have access to clean fuel and, in the context of northern China, heating facilities, have attracted less attention. Here *relative* energy poverty is likely to have very different characteristics, particularly in northern Chinese cities where low winter temperatures necessitate heating provision. The analysis that follows is, to our knowledge, the first detailed study of vulnerability to energy poverty with regards to heating in urban areas in northern China.

4. The case study of heating in Beijing, China

Depending upon the climate zone, specific requirements exist in China regarding domestic energy infrastructure and energy efficiency (Hong et al. 2015). In northern China in the Cold and Severe Cold climate zones, the Huai River Heating Policy makes the provision of state-subsidised heating to all households a legal requirement (Xiao et al. 2015). 300 million people live in urban areas in the fifteen northern provinces in which the heating policy applies. In comparison to the provision of electricity, which is treated as a national policy concern, the legal obligation for subsidised heating provision has been a largely locally driven initiative (Odgaard 2015). In approximately 80% of households in northern cities, heating is provided by Centralised District Heating (CDH) networks (Xiong et al. 2015), a localised form of distribution that provides continuous and subsidised heating typically when outdoor temperatures fall below 5˚C. Due to the greater need for energy to heat the home during winter months, and the provision of continuous energy at a flat rate promoting inefficient household energy practices, residential energy consumption is much higher per capita in northern Chinese cities (BERC 2016). Heating provision in this context has typically relied upon the bulk burning of coal, making a significant contribution towards the high incidence of localised air pollution during the winter. This has negative implications for resident's health as Chen et al. (2013) calculates that life expectancy is approximately 5.5 years lower in these regions. In response, the Chinese government recently announced significant efforts to tackle air pollution in the "2+26" cities that encompasses Beijing, Tianjin and 26 other cities in the region, including an ambitious five-year plan to convert over half of households to cleaner forms of heating (MEE 2018). However, to date household "gas swaps" that are intended to reduce the role of coal in domestic energy provision have been interrupted by significant price hikes and gas shortages.

Our analysis focuses upon Beijing, the capital city located in the Cold climate zone necessitating extensive CDH provision. Beijing is the world's second most populated city and 21.7 million people live within the municipality. Here, annual variations in temperature are dramatic with winter temperatures during the coldest month fluctuating between -10ºC and 0ºC. The urban heat island effect also has considerable influence on temperature differences between urban areas and surrounding rural areas (Cui et al. 2017). These variations necessitate the energy service of heating, and increasingly cooling, to maintain comfortable temperatures in the home (Li and Yao 2009). Partially attributable to the role of coal-fired CDH in heating homes during winter, dangerous PM 2.5 pollution particles average 73 micrograms per cubic metre annually in Beijing, significantly exceeding the recommended WHO level of 25 micrograms per cubic metre.

This paper investigates vulnerability to energy poverty related to thermal comfort in this context, however it also provides wider insights into the phenomenon across northern urban China. Additionally, the analysis has implications for heating in other regions. Increasingly, with rising living standards, residential heating is a concern in the Hot Summer and Cold Winter climate zone (Guo et al. 2015, Zheng et al. 2014). Here, energy use for heating is low and indoor thermal environments require improvement. Typically, use of heating devices is only partial and intermittent with indoor temperature in unheated homes averaging around 12˚C during winter (Guo et al. 2015) and there is on-going debate about whether district heating should be developed in this region.

5. Methodological approach

In the section that follows we summarise our methodological approach, explaining the use of self-reported perceptions of thermal comfort, a household questionnaire survey and the derivation of a typology of vulnerability to energy poverty using LCA.

Self-reported perceptions of thermal comfort

Expenditure-based indicators are the most common approach to measuring energy poverty, calculating whether a household is energy poor using the proportion of income spent on energy. For example, a 10% indicator is used in some European countries classifying those who spend more than 10% of their income on fuel as energy poor (Boardman 1991, Legendre and Ricci 2015). However, there is no consensus about a universal means of measuring energy poverty owing to geographical variations in the condition (Thomson et al. 2017). As a result, self-report perceptions of thermal comfort have frequently been used, also referred to as consensual indicators (Burholt and Windle 2006, Healy and Clinch 2002, Petrova et al. 2013, Thomson and Snell 2013). Whilst expenditure-based indicators can highlight general trends in energy poverty at a low resolution, self-reported indicators can consider a greater diversity of factors that play an important role in the manifestation of energy poverty in addition to expenditure, including the built environment and access to networked infrastructures and appropriate heating systems (Petrova et al. 2013).

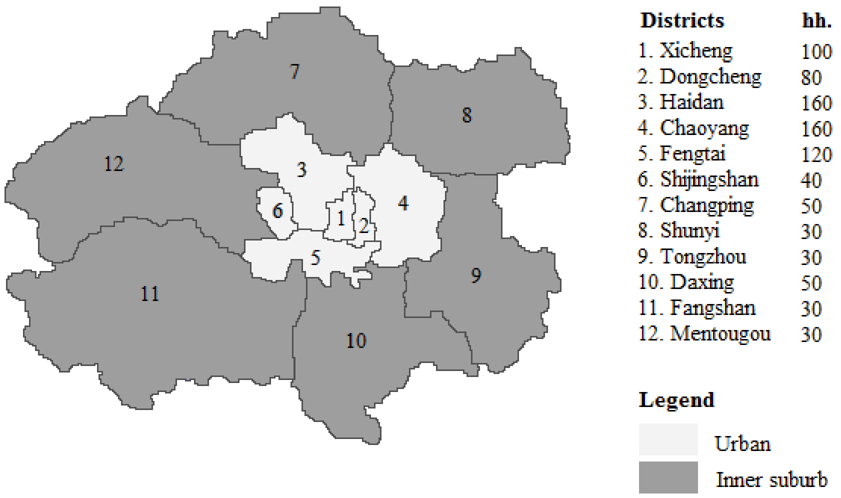

Figure 1. Districts in Beijing included in survey and number of households (hh.) surveyed

Household questionnaire survey

The analysis that follows is based upon a questionnaire survey carried out during the winter of 2013 with 880 randomly-selected households distributed across 12 districts in Beijing (Figure 1). A face-to-face interview was carried out with one household member who provided information about the lifestyle and energy use of the entire household. The survey questions, listed in Table 1, asked households about their domestic energy consumption during winter with a focus upon affordability and energy infrastructures. A question about perceived thermal comfort forms the basis of the energy poverty typology asking: '*How do you like the thermal comfort in your home during winter*?' with four possible responses: *'always cold, never warm'*, '*usually cold, sometimes warm*', '*sometimes cold, usually warm'* and *'never cold, always warm'*. Households that selected '*always cold, never warm'* or '*usually cold, hardly warm'* are most vulnerable to the negative outcomes associated with a cold home being unable to keep their home warm for a significant amount of time during the winter. These households are therefore combined into one '*cold'* category. The result is three thermal comfort categories: '*cold*', *'sometimes cold'* and '*warm'*. Several other variables are selected from the survey to explore the vulnerability factors contributing towards a lack of thermal comfort: household size, household income, energy costs, property type, property size, property age, heating infrastructure and temperature control.

By focusing primarily upon issues of affordability, heating infrastructures and the built environment, some of the multi-faceted vulnerabilities that contribute towards energy poverty that are highlighted in the initial framing are overlooked (Bouzarovski and Petrova 2015). This includes vulnerability due to age, recognising the greater physiological need for heat amongst the very old or the very young; poor health and disability, as these conditions can necessitate a greater physiological need for heat or energy services within the home; and property ownership, influencing ability to invest in energy efficiency. Vulnerability associated with employment status and transience of households would also benefit from further exploration (Browne et al. 2017). The survey has limited scope for understanding the contribution of cultural norms in household energy consumption and perceptions of thermal comfort (Middlemiss and Gillard 2015).

Latent Class Analysis

In addition to descriptive statistics investigating the relationship between perceived thermal comfort and each variable, LCA (McCutcheon 1987) is used to develop a typology of household vulnerability to energy poverty concerning a lack of thermal comfort. LCA is commonly applied to explore poverty and deprivation (Rose et al. 2009, Whelan et al. 2013) allowing for identification of clusters of similar individuals or observations within categorical datasets, described as 'latent classes'. The characteristics of the classes derived are estimated and a probability returned that each household is a member of the class.

Table 1. Household questionnaire survey (translated from mandarin)

Theme Question *Possible answers*
Thermal comfort How do you like the thermal comfort in winter in your home? *[1] always cold, never warm; [2] usually cold, hardly warm; [3] sometimes cold, usually warm; [4] never cold, always warm*
Household size What is the number of family members? *Number of family members*
Building type What is the housing type? *[1] Bungalow; [2] Multi-storey building (under 7 floors); [3] High-rise tower building (over 7 floors); [4] High-rise slab type building (over 7 floors); [5] Villa*
Property size What is the floor area? *Floor area in m2*
Property age What is the construction age of the property? *[1] Before 1985; [2] 1985-1995; [3] 1996 – 2005; [4] After 2005.*
Income What is the total family income? *[1] Below 30k yuan; [2] 30 – 50k yuan; [3] 50 – 100k yuan; [4] 100 – 150k yuan; [5] Over 150k yuan*
Energy price What is the total cost for electricity and gas during the winter period? *元 (yuan)*
Heating infrastructure What is the most frequently used heating equipment? *[1] no heating equipment; [2] community district heating; [3] natural gas boiler; [4] Room air-conditioner; [5] Electric radiator; [6] Other (e.g. floor heating, heater fan, electric head heater, electric heat blanket)*
Temperature control If you use a centralized heating system, is it manipulative? *[1] not adjustable; [2] adjustable*

6. Descriptive statistics

Descriptive statistics related to the questionnaire are presented in Table 2, including a breakdown of the relationship of each variable with perceptions of thermal comfort.

Thermal comfort

Of the households surveyed 11.9% expressed that they were cold during the winter whilst 42.5% were sometimes cold. Thus, 54.4% of households were vulnerable to the negative effects of a lack of thermal comfort. 45.6% expressed that they were consistently warm.

Affordability

59% of households who paid over 6000 RMB (the highest energy cost bracket in the survey) to supply their home with energy identified as warm (Figure 2). This suggests that having the opportunity to pay for more expensive energy infrastructures or having the financial ability to pay a high price for energy (primarily gas) reduces vulnerability to a lack of thermal comfort. On average those that expressed that they were cold pay a low price for energy, typically 2000-3000 RMB over the winter months. Concerning affordability due to household income, between the lowest and highest income brackets there is a steady decline in the percentage of households feeling consistently cold. In the lowest income bracket, 0-30000 RMB, 19% of households recorded feeling cold. In the highest income bracket, over 150000 RMB, 7% of households felt cold. However, this trend was not repeated in the data for households that sometimes felt cold. In the highest bracket, 53% of households recorded feeling cold or sometimes cold, similar to the other income brackets where the percentage of households feeling cold or sometimes cold fluctuated between 51% – 59%. A high income therefore provides greater protection from always feeling cold but fails to protect a household completely from a lack of thermal comfort.

Built environment

Bungalows have the highest proportion of households that express feeling cold (25.98%) (Figure 3, Figure 5). In comparison, in high-rise slab-type buildings only 3.3% of households reported being cold. The age of the property also contributed to vulnerability, suggesting that newly built properties provide greater protection from the cold. 18.8% of properties built prior to 1985 (primarily bungalows) reported being cold. This figure was considerably lower in homes built more recently, 1985-1995 (9.9%), 1996-2005 (7.7%) and 2006-current (9.8%).

Heating infrastructure

A natural gas boiler provides the greatest protection from a lack of thermal comfort with only 7.3% of households feeling cold and 19.5% sometimes feeling cold (Figure 4). The existence of CDH in the home was the second most successful heating infrastructure in relation to thermal comfort, however 52.7% of these households reported feeling cold or sometimes cold. An air conditioner (AC), electric radiator or other form of heating were all associated with high levels of thermal discomfort. Of the households using AC for heating, 36.45% felt cold, whilst in households using an electric radiator 33.3% felt cold.

Table 2. Surveyed households categorised by questionnaire variable

Category	Hh (count)	Hh (%)	Cold (count)	Cold (%)	Sometimes (count)	Sometimes (%)	Warm (count)	Warm (%)
Thermal comfort								
Cold	104	11.9	-	-	-	-	-	-
Sometimes cold	374	42.5	-	-	-	-	-	-
Warm	402	45.6	-	-	-	-	-	-
Household size (persons)								
0 – 2	209	23.8	33	12.6	104	39.7	125	47.7
3 – 4	572	65.0	60	11.5	221	42.5	239	46.0
5 +	99	11.3	12	12.2	49	50.0	37	37.8
Income (RMB)								
0 – 30000	95	10.8	18	18.9	34	35.8	43	45.3
30001 – 50000	279	31.7	35	12.5	129	46.2	115	41.2
50001 – 100000	350	39.8	40	11.4	139	39.7	171	48.9
100001 – 150000	114	13.0	9	7.9	53	46.5	52	45.6
150001 +	42	4.8	3	7.1	19	45.2	20	47.6
Energy cost (RMB)*								
0 – 1000	85	9.7	10	11.8	39	45.9	36	42.4
1000 – 2000	192	21.8	22	11.5	77	40.1	93	48.4

2000 – 3000	295	33.5	39	13.2	126	42.7	130	44.1
3000 – 4000	183	20.8	15	8.2	81	44.3	87	47.5
4000 – 5000	59	6.7	10	16.9	26	44.1	23	39.0
5000 – 6000	34	3.9	6	17.6	15	44.1	13	38.2
6000+	32	3.6	3	9.4	10	31.3	19	59.4
Building type								
Multi-storey	564	64.1	66	11.7	230	40.8	268	47.5
High-rise tower	163	18.5	13	8.0	70	42.9	80	49.0
Bungalow	93	10.6	24	25.8	49	52.7	20	21.5
High-rise slab	60	6.8	2	3.3	25	41.7	33	55.0
Villa	0	0.0	0	0.0	0	0.0	0	0.0
Property size								
0 – 50	209	23.8	37	17.7	86	41.1	86	41.1
50 – 100	572	65.0	58	10.1	248	43.4	266	46.5
100 – 150	99	11.3	10	10.1	40	40.4	49	49.5
Property age								
Pre-1985	271	30.8	51	18.8	123	45.4	97	35.8
1986 – 1995	273	31.0	27	9.9	103	37.7	143	52.4
1996 – 2005	285	32.4	22	7.7	127	44.6	136	47.7
2006 – Current	51	5.8	5	9.8	21	41.2	25	49.0
Heating infrastructure								
None	0	0.0	0	0.0	0	0.0	0	0.0
CDH	745	84.7	76	10.2	318	42.7	351	47.1
Natural gas boiler	41	4.7	3	7.3	8	19.5	30	73.2
Room AC	11	1.3	4	36.4	4	36.4	3	27.3
Electric radiator	51	5.8	17	33.3	25	49	9	17.6
Other	32	3.6	5	15.6	19	59.4	8	25.0
Temperature control								
Not adjustable	712	80.9	73	10.3	304	42.7	335	47.1
Adjustable	168	19.1	32	19.0	70	41.7	66	39.3

**Total cost of electricity and gas for a household during the winter period.*

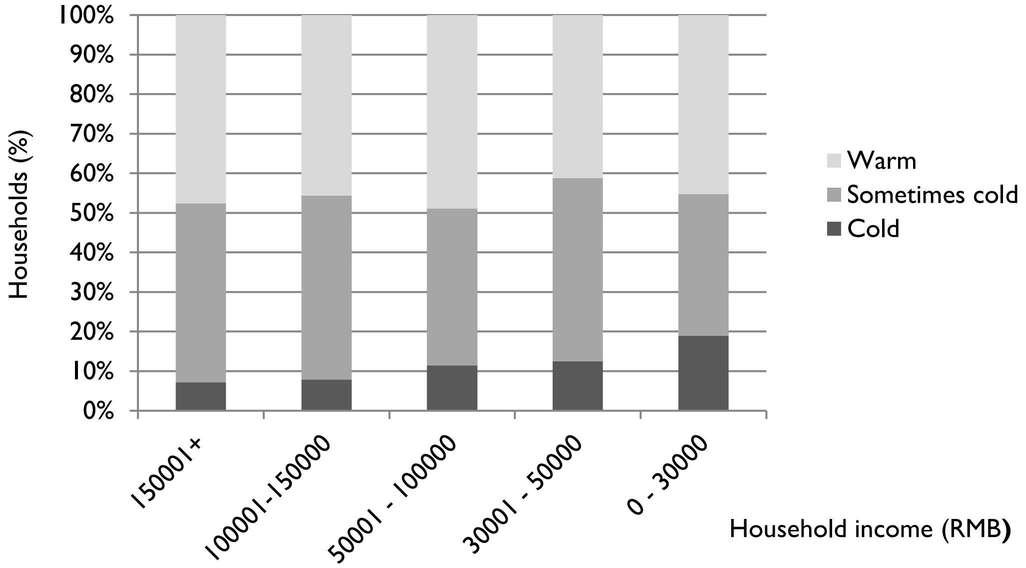

Figure 2. Distribution of perceptions of thermal comfort in winter by annual household income

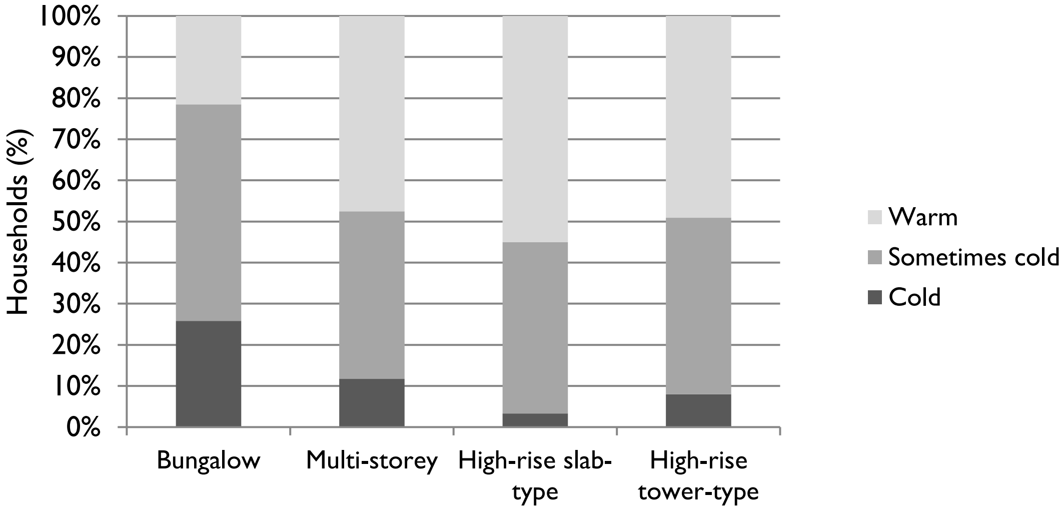

Figure 3. Distribution of perception of thermal comfort in winter by building type

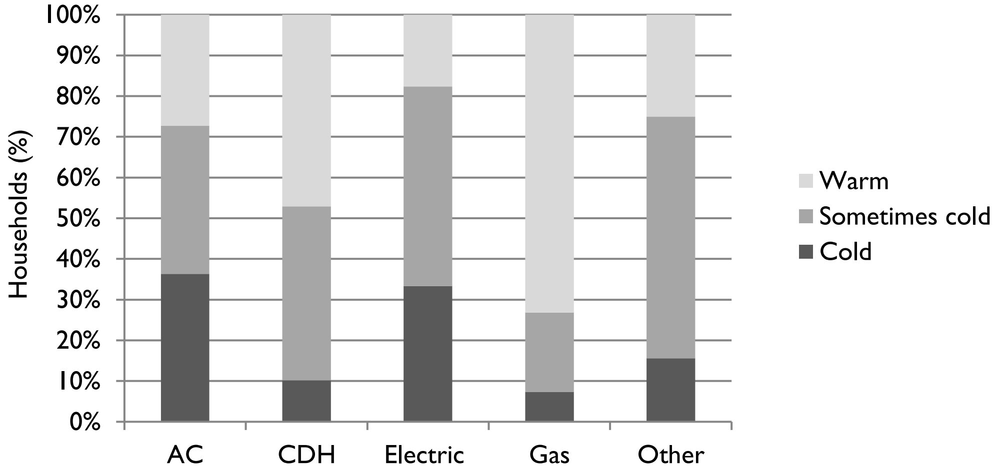

Figure 4. Distribution of perception of thermal comfort in winter by heating type

Figure 5. Example of properties in Beijing categorised as a bungalow (Source: Author)

7. Deriving a typology of vulnerability to energy poverty in relation to thermal comfort

To derive the typology of vulnerability to energy poverty concerning a lack of thermal comfort, several LCA model iterations were carried out with one, two, three, four, five and six classes. The results of the model fit for each iteration are summarised in Table 3. The most appropriate LCA model contains four classes, each representing a group of households with similar characteristics from the survey. The four-class model is considered most appropriate due to its low Akaike's Information Criterion (AIC) and Bayesian Information Criterion (BIC) values, and consideration of the usefulness of the LCA results in practice. Conditional probabilities yielded by the four-class model are displayed in Table 4. These indicate the probability of a household having a certain characteristic given that it already has another specified characteristic, allowing for households to be grouped into classes with similar attributes. In this analysis, conditional probabilities for a variable category that exceed 0.25 are included in the class description, although in some instances where the percentage of households in a category are very low (for example, heating using AC) it is appropriate for lower values to be considered. A description of the characteristics typical of households within each class is provided in Table 5.

Table 3. Results of model fit for LCA model iterations

	One class	Two class	Three class	Four class	Five class	Six class
AIC	15384.04	13984.55	13414.73	13213.86	13059.38	13014.86
BIC	15503.54	14228.32	13782.78	13706.20	13675.99	13755.75
Likelihood ratio	4932.56	3481.07	2859.25	2606.38	2399.90	2303.38

The class reporting greatest vulnerability to a lack of thermal comfort is class three. Class three accounts for approximately 10.7% of households. Households in class three commonly report being cold (0.27) or sometimes cold (0.57). Most of these households live in a bungalow (0.97) and none of the households use the CDH network or a natural gas boiler, instead relying upon a room AC (0.1170), electric radiator (0.54) or other appliance (0.34) to heat the home. As a result, all households have control over the temperature in their home, in contrast to classes two and four that use CDH and have no control. Many of the buildings are built prior to 1985 (0.65), the oldest category, and tend to be small, with the majority less than 50m^2 in area (0.76). Class three households tend to have a relatively low income, but the reported price of energy is also relatively low.

The class which reports the least vulnerability in relation to thermal comfort is class one. Class one accounts for approximately 4.7% of households in the sample. In this class, households most commonly report being warm (0.73). All properties in this class are multi-storey and usually built between 1996-2005 (0.59) or since 2005 (0.32). Natural gas boilers are used for heating which offer households greater control over temperature. The price of energy is relatively high in class one, with many households paying over 6000 RMB annually (0.41) however income also tends to be relatively high.

Two classes are also identified in which households have some vulnerability to thermal comfort, class two and class four. In class two, which accounts for 62.8% of the survey sample, households most commonly report being sometimes cold (0.42) or warm (0.47). In class four, which accounts for 21.8% of the survey sampled, households commonly reported being sometimes cold (0.46) or warm (0.48). Both classes rely entirely upon CDH for heating which largely means that the household has no control over indoor temperature. Class two has a high proportion of multi-storey buildings (0.79) whilst class four includes both multi-storey buildings (0.45) and high-rise tower-type buildings (0.46). Both classes have average energy costs, but class four tends to have a higher average income than those in class two. In addition, properties in class four tend to be larger, often over 100m^2 (0.38), whilst none of the households in class two fall into this category.

Table 4. Latent class conditional probabilities and sizes for the four-class model

	Class 1	**Class 2**	**Class 3**	**Class 4**
Thermal comfort				
Cold	0.0732	0.1135	0.2766	0.0688
Sometimes cold	0.1951	0.4167	0.5106	0.4562
Warm	0.7317	0.4698	0.2128	0.4750
Household size (person)				
1 - 2	0.2195	0.3658	0.2660	0.1335
3-4	0.5854	0.5669	0.5851	0.6641
5+	0.1951	0.0672	0.1489	0.2024
Household income (RMB)				
0 – 30000	0.0244	0.1213	0.1383	0.0724
30001 – 50000	0.0732	0.3693	0.3511	0.2016
50001 – 100000	0.5366	0.3870	0.4043	0.3956
100001 – 150000	0.3171	0.0803	0.0851	0.2534
150001 +	0.0488	0.0420	0.0213	0.0770
Household energy costs (RMB)				
0 – 1000	0.0488	0.0854	0.3617	0.0091
1000 – 2000	0.0244	0.2821	0.1596	0.1039
2000 – 3000	0.1707	0.4141	0.1064	0.2549
3000 – 4000	0.1463	0.1691	0.0957	0.3882
4000 – 5000	0.0732	0.0376	0.1170	0.1263
5000 – 6000	0.1220	0.0072	0.1064	0.0784
6000+	0.4146	0.0045	0.0532	0.0391
Building type				
Multi-storey	1.0000	0.7868	0.0213	0.4467
High-rise tower-type	0.0000	0.1345	0.0000	0.4621
Bungalow	0.0000	0.0036	0.9681	0.0000
High-rise slab-type	0.0000	0.0750	0.0106	0.0912
Property size (m²)				
100 +	0.4146	0.0000	0.1064	0.3756
50 - 100	0.5122	0.7578	0.1277	0.6244
0 - 50	0.0732	0.2422	0.7660	0.0000

Property age				
Pre-1985	0.0976	0.3723	0.6489	0.0000
1985 - 1995	0.0000	0.4066	0.0638	0.2194
1996 - 2005	0.5854	0.2211	0.0957	0.6763
2006 - Current	0.3171	0.0000	0.1915	0.1043
Heating infrastructure				
Central district heating	0.0000	1.0000	0.0000	1.0000
Natural gas boiler	1.0000	0.0000	0.0000	0.0000
Room AC	0.0000	0.0000	0.1170	0.0000
Electric radiator	0.0000	0.0000	0.5426	0.0000
Other	0.0000	0.0000	0.3404	0.0000
Temperature control				
Not adjustable	0.0000	0.9605	0.0000	0.9417
Adjustable	1.0000	0.0395	1.0000	0.0583
Est. class population shares	0.0466	0.6288	0.1068	0.2178
Predicted class membership*	0.0466	0.6466	0.1068	0.2000

Note: Observations n = 880, estimated parameters n = 111, residual degrees of freedom: 77, maximum log-likelihood: -6503.932, AIC: 13213.86, BIC: 13706.2

** Modal posterior probability*

Table 5. Typology of household vulnerability to energy poverty concerning a lack of thermal comfort (Descriptions are relative to other classes within the typology)

	Lack of thermal comfort	Description of typical household
Class one	'Warm'	Class one households consist of between three and four persons in a medium or large sized property in a multi-storey building built since 1996. They have a higher than average income. Heating is provided in the home by a natural gas boiler that offers control over the indoor temperature and the price of energy is relatively high.
Class two	'Warm' or 'Sometimes cold'	Class two households consist of between one and four persons living in a multi-storey building in a medium size property built prior to 1995. They have a low to medium income. Heating is provided by a central district heating system that offers no control over the indoor temperature and the price of energy is relatively low.
Class three	'Cold' or 'Sometimes cold'	Class three households consist of between one and four persons in a small bungalow built prior to 1985. They have a low to medium income. Heating is provided by an electric radiator, room AC or other energy infrastructure, each of which offers control over the indoor temperature. The energy price is relatively low.

Class four	'Warm' or 'Sometimes cold'	Class four households consist of three or four persons living in a large or medium sized property in a multi-storey building or high-rise tower-type, built between 1996 and 2005. They have a medium income. Heating is provided in the home by centralised district heating which offers no control over the indoor temperature and the price of energy is medium.

8. Identifying vulnerability factors in relation to thermal comfort in northern Chinese Cities

Our typology of vulnerability to energy poverty due to a lack of thermal comfort demonstrates that significant inequalities exist in access to adequate heating in households in cities in northern China. Drawing on the typology, we now identify and discuss the contribution of several vulnerability factors towards a lack of thermal comfort within this geographical context: the negligible contribution of energy price, the significant contribution of inappropriate networked infrastructures and poor quality, inefficient built environment, the role of household income in access to these infrastructures, and the part played by a households control over networked infrastructures and heating. In doing this, we identify synergies with experience of energy poverty in other geographical contexts.

8.1 Energy subsidies partially negating the role of high energy prices in energy poverty

Studies of energy poverty in the Global North have often focused upon high energy prices as a primary driver of the condition, necessitating the presence of energy poverty on policy agendas (Boardman 2010, Liddell et al. 2012). For example, high energy prices have also been pivotal in energy poverty in post-communist states of Central and Eastern Europe where, during the past two decades, extensive reforms in the energy sector have led to the privatisation of state-owned utilities and price increases (Buzar 2007).

In contrast, our typology suggests that energy price is not one of the significant vulnerability factors contributing to energy poverty in this case study. In cities and towns in colder regions in China, CDH remains one of the largest forms of welfare providing low cost and stable heating (The World Bank 2014). Heating is provided continuously throughout winter via extensive state-owned CDH networks to most homes (approximately 80% of homes have access to CDH in Beijing and 84% of homes in the survey). This is paid for according to total floor space in the property and is highly subsidised (Beijing Municipal Government 2017). The heating fee per square meter is identical, disregarding the thermal properties of the building. Even amongst households that do not have access to the CDH and are most vulnerable to a lack of thermal comfort (class three) energy prices are relatively low as the cost of electricity, one of the most common forms of heating provision besides the CDH, is also subsidised so as not to reflect the high production costs. In a study of domestic energy consumption across China, Hu et al. (2017) found that energy price and economic incentives did not tend to influence energy consumption. There is some concern, however, that the low energy prices in households without access to the CDH could be attributed to an inability to afford sufficient energy, even at subsidised rates. In this case households are deliberately under consuming, particularly if they are unemployed or socially precarious (Browne et al. 2018, Huang and Yi 2014). However, this requires further exploration beyond the scope of our survey.

Whilst the state-subsidisation of heating during the winter might be anticipated to buffer households from experiencing energy poverty, our analysis suggests this is not the case. A significant proportion of the households sampled express that they were cold (12%) or sometimes cold (42.2%) and thus at risk. Alone, subsidised heating costs are insufficient to prevent households that lack access to appropriate networked infrastructures and a high quality, energy efficient built environment from being cold.

8.2 Inequalities in the quality of the built environment and networked infrastructures

Researchers have often drawn attention to the importance of infrastructure in enhancing energy poverty, including the role of the built environment (Boardman 2010, Buzar 2007, Hong et al. 2009, Wilkinson et al. 2007) and networked energy infrastructures (Harrison and Popke 2011). Our typology of thermal comfort in households in Beijing highlights the importance of access to an efficient and high quality, built environment for the energy services available to the home to be used in the most efficient manner possible.

The built environment has been a key feature of energy poverty research, inherently connected with historical and institutional factors. In northern China, thermal insulation is historically poor with buildings requiring 50-100% more energy for space heating than those in European countries with comparable climates (Liu et al. 2011, The World Bank 2014). In class three of the typology (the class with greatest risk of a cold home during winter) almost all properties are bungalows, a majority of which were built prior to 1985 prior to housing reforms and are therefore not part of the CDH network.

The typology also identifies the inability to access networked energy infrastructures as one of the strongest predicators of a lack of thermal comfort. Most households belonging to class three rely upon an electric radiator, AC or other infrastructure as the primary means of heating. Exclusion from networked energy infrastructure that supply homes in other classes, most commonly the CDH and additionally gas, generates significant inequalities in achieving sufficient warmth. Inequalities in the provision of networked infrastructure in urban areas and the uneven socio-spatial development of utilities are identified elsewhere, often driven by energy markets (Graham and Marvin 2001). In other geographical contexts in which the privatisation of utilities and networked infrastructure provision has occurred, this has led to the creation of marginalised spaces and premium networked spaces. More lucrative consumers in utility markets that are easier and cheaper to supply have been 'cherry-picked', with a simultaneous 'social dumping' of more marginal domestic consumers (Graham and Marvin 1994).

In Beijing, energy price does not appear to play the same role in generating such inequalities due to state subsidies. Instead, the inequalities apparent in our typology in access to networked infrastructures are inherently linked with the built environment. The age of bungalows means that they tend to predate the significant investment made in CDH. These households must then rely upon an electric radiator, AC or other form of heating that is often insufficient to heat an inefficient bungalow to the required standard. This is due to a mismatch between the infrastructures available and the indoor space. For example, an AC is not designed to heat but to cool whilst individual infrastructures are more likely to heat individual rooms rather than the entire house. This mismatch is evidenced elsewhere as Rudge (2012) draws attention to the historical legacy of housing built in England prior to 1920 that were not designed with convective central heating in mind, the primary mechanism of heating in England today.

8.3 Socio-technical relations between household income and energy infrastructures

The disparities in the quality of the built environment and availability networked heating infrastructures identified can also be linked to increasing inequalities in housing provision in urban China more generally. Since 1987, both economic and housing reforms have transformed the provision of housing. From 1949 until 1987 the Communist government treated housing as a form of welfare with publicly-owned rental properties dominating the housing stock. Properties were allocated according to employment rank, marital status and household size (Wang and Murie 2000, Logan et al. 1999). In Beijing, this altered the spatial structure of the city producing a historical core characterised by poor-quality, single-storey housing, surrounded by a zone of public work-units that provided heavily subsidised accommodation to their employees, and finally a wider suburban zone of work-units engaged in different industrial activities (Wang and Murie 2000). Due to housing shortages in 1985, significant housing reforms were triggered encouraging the marketization of the sector. A change in approach to land markets allowed for the development of commercial residential housing and a greater stock of commercial, rather than government owned, housing (Yeh and Wu 1996). The government actively promoted homeownership though incentives and subsidies including the subsidised sale of government owned properties (Yi and Huang 2014). Subsequent commercial housing programmes have produced housing of different standards, the most popular designs being multi-storey housing of between four and six floors and a small number of high-rise blocks. Wang and Murie (2000) describe this housing reform as the largest programme of privatisation this century.

These changes have led to unprecedented increases in housing consumption and ownership (Huang and Clark 2002, Yi and Huang 2014) and subsequently improved living conditions for urban residents who have greater choice of dwelling, tenure and neighbourhoods (Huang and Jiang 2009). The reforms have increased average floor areas of dwellings, addressing previous issues of overcrowding in urban residential properties. However, when combined with institutional mechanisms such as *hukou,* the household registration system that registers persons to specific urban or rural districts, these reforms have also created significant inequalities (Afridi et al. 2015, Huang et al. 2014). There exists a differential ability to pay for housing quality, producing new enclaves of private housing for the wealthy (Hu and Kaplan 2001, Wang and Murie

2000). For example, Hu and Kaplan (2001) document the rise of a new urban affluent that can take advantage of greater choice in housing, enhancing socio-spatial segregation of residents in Beijing.

The findings related to property age within our typology demonstrate that the newest housing, built since 1985 and the housing reforms, offers considerably more protection from energy poverty. Newer housing tends to be of better quality and access to it is market-driven. Therefore, a higher income reduces a household's vulnerability as they can invest in newer housing, enabling them to access more appropriate networked infrastructures in a high quality, energy efficient property. In comparison to energy poverty documented in the Global North, the importance of income is less concerned with the inability of a household to afford high energy prices, and instead is primarily concerned with an inability to invest in infrastructures that can protect them from the cold. This trend echoes the high incidence of energy poverty amongst low income groups in the Global North who do not have the capital to invest in energy efficient properties or retrofit measures, including those with a disability (Snell et al. 2015), reliant on a state pension (O'neill et al. 2006) or in privately rented accommodation (Ambrose 2015).

8.4 Flexibility and control of domestic energy infrastructure

Chappells (2011) acknowledges that a lack of control over individual circumstances can also cause thermal discomfort. Although households in Beijing on the CDH network are provided with energy at a fixed rate, a factor that might be anticipated to shield a household entirely from energy poverty related to thermal comfort given the constant access to heating provision without extra charge, our analysis highlights two classes composed entirely of households using CDH (class two and class three) that still contain households that perceive themselves to be cold during the winter (7% and 12% respectively). Temperature control in many northern Chinese households is reputedly poor, with only certain rooms heated to a sufficient temperature, whilst others are too warm encouraging energy inefficient practices (Liu et al. 2011). This is due to a lack of control devices or a lack of incentive to control heating usage due to the heating fee based upon floor space (Liu et al. 2011). Lack of control over energy services, particularly temperature, has also been linked with energy poverty in apartment blocks reliant on CDH in formerly communist Central and Eastern European countries including Hungary (Herrero and Urge-Vorsatz 2012), Romania (Poputoaia and Bouzarovski 2010), Ukraine (Petrova et al. 2013) and the Czech Republic (Bouzarovski et al. 2016).

9. Conclusions

Whilst vast improvements in the quality of living have been made in China in recent decades with respect to the alleviation of poverty, our analysis highlights the existence of significant inequalities in relation to the provision of the energy service of heating in urban areas within the Cold climate zone. In the case study city of Beijing a significant proportion of households are unable to secure adequate heating in their home to ensure their thermal comfort and are therefore likely to be energy poor. In contrast to existing research in neoliberal economies in the Global North, the price of energy (despite being high in China relative to some household incomes) is not a significant vulnerability factor with regards to energy poverty, given the continued political will for welfare relating to domestic energy provision in northern China. However, despite the provision of universal state subsidies for heating in urban areas in colder regions, a mechanism that might be anticipated to buffer households from experiencing energy poverty, such subsidies are insufficient to shield from the cold those households that lack access to appropriate networked infrastructures and a high quality, energy efficient, built environment. The condition identified in this context is therefore primarily a poverty of infrastructure. Domestic, socio-technical configurations of income and infrastructure considerably enhance or decrease a household's vulnerability to energy poverty, with the privatisation of the housing market over several decades generating significant inequalities in ability to purchase high quality, energy efficient properties.

In addition to exploring vulnerability to energy poverty in a novel, geographical context, this analysis represents the first application of LCA to the exploration of energy poverty. Our methodological approach effectively illustrates the relative contribution of a range of vulnerability factors towards a lack of thermal comfort, allowing for the development of a succinct typology from a complex, multi-faceted questionnaire dataset. This approach could be applied in various geographical contexts and at different scales, including transnational or international comparisons, or in more localised analyses. The typology of vulnerability to energy poverty in relation to thermal comfort created using this methodology identifies a subset of households with relatively high vulnerability to energy poverty: households that live in older bungalows excluded from the CDH network and reliant on a low household income. To a lesser degree, vulnerability is also identified amongst some households that live in properties reliant upon inflexible CDH infrastructures to provide heating, over which they have little control.

Whilst extraordinary progress has been made across China nationally with regards to access to electricity (Bhattacharyya and Ohiare 2012, Wang et al. 2015), policy-making needs to reach beyond energy poverty as a lack of access (as often focused upon in the context of the Global South) and begin to address some of the deep inequalities in domestic energy provision that exist in more affluent city regions in China. In our case study of heating in Beijing in northern urban China we have highlighted a subset of households that experience vulnerability to energy poverty, relative to neighbouring households, that can be attributed to inappropriate networked infrastructures and a poor quality built environment. By tackling the issue of energy poverty in this arena, policy-makers can simultaneously fulfil social justice imperatives, climate change mitigation goals and targets regarding localised air pollution.

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